Tha3_1

ON-WAFER NOISE-PARAMETER MEASUREMENTS AT NIST

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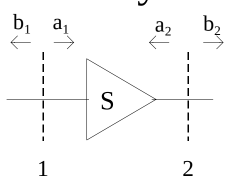
OUTLINE

- Theoretical framework, wave representation of noise matrix
- On-wafer calibration, reference planes, probe corrections
- Noise parameter measurement method
- Uncertainty analysis
- Results for a CMOS (NMOS) transistor
- Summary

FRAMEWORK

- Formalism follows wave representation of noise correlation matrix
- Linear two-port (amp, transistor, attenuator,…) described by



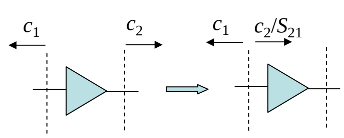
$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} + \begin{pmatrix} c_1 \\ c_2 \end{pmatrix}$$

- Intrinsic noise correlation matrix defined by

$$\hat{N}_{ij} = \left\langle c_i c_j^* \right\rangle$$

Normalization: $|c|^2$ = spectral power

- 4 independent parameters: N_{11}, N_{22}, complex N_{12}
- Convenient to define variables referred to input by scaling $c_2 \to c_2/S_{21}$,



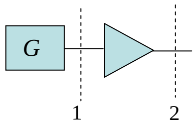
$$k_B X_1 \equiv \left\langle |c_1|^2 \right\rangle = \hat{N}_{11}$$

$$k_B X_2 \equiv \left\langle \left| \frac{c_2}{S_{21}} \right|^2 \right\rangle = \frac{\hat{N}_{22}}{|S_{21}|^2}$$

$$k_B X_{12} \equiv \left\langle c_1 \left(\frac{c_2}{S_{21}} \right)^* \right\rangle = \frac{\hat{N}_{12}}{S_{21}^*}$$

- X's have dimensions of temperature.

- In terms of *X*'s,

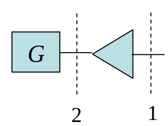


G_{av}

$$T_2 = \frac{|S_{21}|^2}{\left(1-|\Gamma_2|^2\right)}\left\{\frac{\left(1-|\Gamma_G|^2\right)}{|1-\Gamma_G S_{11}|^2} T_G + \left|\frac{\Gamma_G}{1-\Gamma_G S_{11}}\right|^2 X_1 + X_2 + 2\mathrm{Re}\left[\frac{\Gamma_G X_{12}}{1-\Gamma_G S_{11}}\right]\right\}$$

n.b.: linear fit if just forward configuration.

- Also measure reverse configuration,



$$T_1 = \frac{1}{\left(1-|\Gamma_1|^2\right)}\left\{\frac{\left(1-|\Gamma_G|^2\right)|S_{12}|^2}{|1-\Gamma_G S_{22}|^2} T_G + \left|\frac{S_{12}S_{21}\Gamma_G}{1-\Gamma_G S_{22}}\right|^2 X_2 + X_1 + 2\,\mathrm{Re}\left[\frac{S_{12}S_{21}\Gamma_G X_{12}^*}{1-\Gamma_G S_{22}}\right]\right\}$$

- Can relate *X*'s to IEEE parameters,

$$T_2 = G_{av}\left(T_G + T_e\right) \qquad T_e = T_{\min} + t\frac{|\Gamma_G - \Gamma_{opt}|^2}{\left(1-|\Gamma_G|^2\right)|1+\Gamma_{opt}|^2} \qquad t = \frac{4R_n T_0}{Z_0}$$

X's → IEEE

$$t = X_1 + |1+S_{11}|^2 X_2 - 2\,\mathrm{Re}\left[(1+S_{11})^* X_{12}\right],$$

$$T_{e,\min} = \frac{X_2 - |\Gamma_{opt}|^2\left[X_1 + |S_{11}|^2 X_2 - 2\,\mathrm{Re}\left(S_{11}^* X_{12}\right)\right]}{\left(1+|\Gamma_{opt}|^2\right)},$$

$$\Gamma_{opt} = \frac{\eta}{2}\left(1 - \sqrt{1 - \frac{4}{|\eta|^2}}\right),$$

$$\eta = \frac{X_2\left(1+|S_{11}|^2\right) + X_1 - 2\,\mathrm{Re}\left(S_{11}^* X_{12}\right)}{\left(X_2 S_{11} - X_{12}\right)}.$$

IEEE ⟶ X's

$$X_1 = T_{e,\min}\left(|S_{11}|^2 - 1\right) + \frac{t\,|1 - S_{11}\Gamma_{opt}|^2}{|1+\Gamma_{opt}|^2},$$

$$X_2 = T_{e,\min} + \frac{t\,|\Gamma_{opt}|^2}{|1+\Gamma_{opt}|^2},$$

$$X_{12} = S_{11} T_{e,\min} - \frac{t\,\Gamma_{opt}^*\left(1 - S_{11}\Gamma_{opt}\right)}{|1+\Gamma_{opt}|^2}.$$

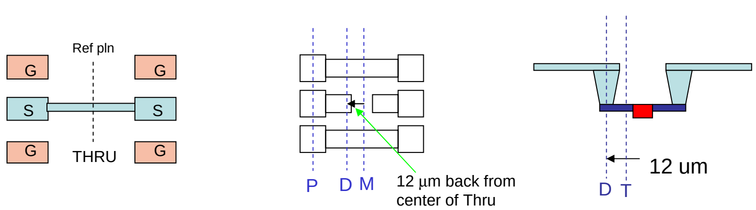
Notes: $X_2 = T_{e,0}$

Bound implied by $X_1 \geq 0$

NIST NOISE

CALIBRATION, REFERENCE PLANES

- Use on-wafer multiline TRL calibration with on-wafer standards. (Could use a compact cal set to save real estate.)
- Reference plane defined by center of THRU (M); can be translated since calibration also characterizes transmission line.



NIST NOISE

Noise Measurement

- NIST uses a (total power) radiometer-based method similar to its method for packaged amplifiers.
- Ambient & cryogenic (liquid nitrogen) primary standards.


$u_{TCry} \approx 0.65$ K

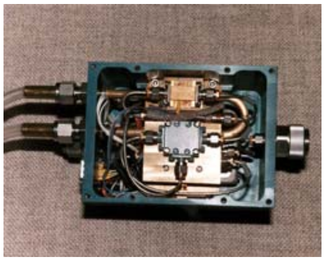
$u_{TAmb} \approx 0.1$ K

NIST NOISE

Noise Measurement (cont'd)

- Radiometer, switch housing with ambient standard.

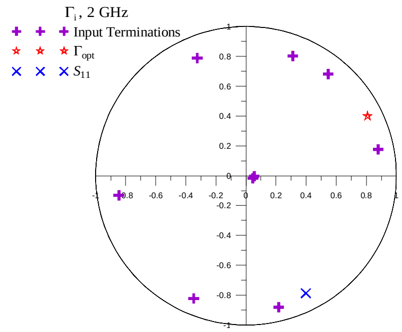




NIST NOISE

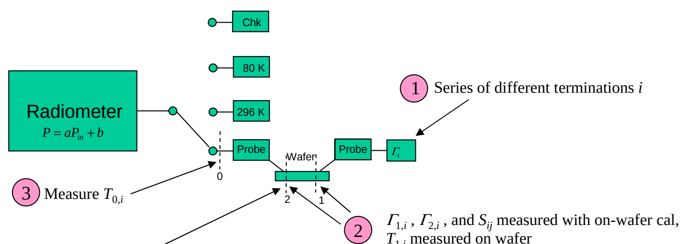
On-Wafer Setup

- S-parameters measured on VNA, noise on radiometer.
- Use discrete terminations on input: slow, painful, but repeatable & flexible. (Choice of input states still under study.)



NIST NOISE

•Measurement method (similar to packaged amplifiers):



4 Compute $T_{2,i}$: $T_0 = \alpha_{02} T_2 + (1-\alpha_{02}) T_{amb}$ so $T_{2,i} = \dfrac{T_{0,i} - (1-\alpha_{02,i}) T_{amb}}{\alpha_{02,i}}$

where $\alpha_{02.i} \equiv \dfrac{P_0^{avail}}{P_2^{avail}} = \dfrac{|S_{21}(02)|^2 \left(1-|\Gamma_{2,i}|^2\right)}{|1-\Gamma_{2,i} S_{11}(02)|^2 \left(1-|\Gamma_{0,i}|^2\right)}$

5 Measure T_{rev} = T_1 in reverse configuration

6 (Weighted) Fit to $T_{2,i} = \dfrac{|S_{21}|^2}{\left(1-|\Gamma_{2,i}|^2\right)} \left\{ \dfrac{\left(1-|\Gamma_{1,i}|^2\right)}{|1-\Gamma_{1,i} S_{11}|^2} T_{1,i} + \left| \dfrac{\Gamma_{1,i}}{1-\Gamma_{1,i} S_{11}} \right|^2 X_1 + X_2 + 2\,\mathrm{Re}\left[\dfrac{\Gamma_{1,i} X_{12}}{1-\Gamma_{1,i} S_{11}} \right] \right\}$

and

$$T_1(rev.config) = \frac{1}{\left(1-|\Gamma_1|^2\right)} \left\{ \frac{|S_{12}|^2 \left(1-|\Gamma_{2,L}|^2\right)}{|1-\Gamma_{2,L} S_{22}|^2} T_{2,L} + \left| \frac{S_{12} S_{21} \Gamma_{2,L}}{1-\Gamma_{2,L} S_{22}} \right|^2 X_2 + X_1 + 2\,\mathrm{Re}\left[\frac{S_{12} S_{21} \Gamma_{2,L} X_{12}^{\,*}}{1-\Gamma_{2,L} S_{22}} \right] \right\}$$

NIST NOISE

UNCERTAINTIES

- Follow ISO Guide to Uncertainty in Measurement (GUM)
- Type A (statistical): obtained in the fitting process, from covariance matrix V_{ij}: $u_A(i) = \sqrt{V_{ii}}$
- Type-B uncertainties are all other uncertainties, i.e., not evaluated by statistical means.
- We "know" uncertainties in underlying quantities ($T_{G,i}$, $\Gamma_{G,i}$, $T_{out,i}$, S, T_{amb} , …); want the resulting uncertainties in noise parameters.
- Estimate them with a Monte Carlo program

- Values used for underlying uncertainties:

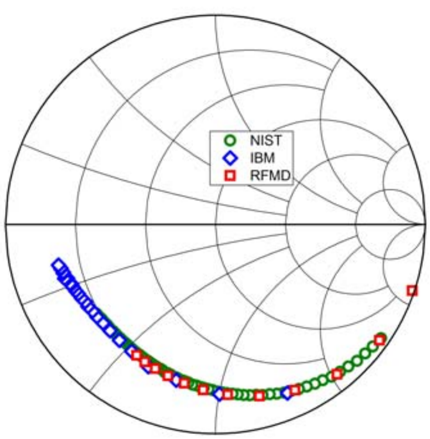
	σ_{cor}	σ_{uncor}
$\Gamma_{G,i} \leq 0.005$:	0.003	0.004
$\Gamma_{G,i} > 0.005$:	0.003	0.004
S_{21}:	0.003	0.004
T_{amb} :	0.0	0.5 K (rect. distr.)
$T_{in,hot}$:		1 %
$T_{out,meas}$:	0.8 %	0.6 %

- Will see resulting uncertainties in noise parameters below.

SOME RESULTS

- Measurements & comparisons done as part of "Kelvin Project," with IBM & RF Micro Devices (RFMD)
  - 128×3×0.12 NMOS device
  - 128 fingers of polysilicon over
  - 3 µm wide active channel
  - 0.12 µm gate length
  - fabricated in 0.13 µm technology (by IBM)
- Bias:
  - drain voltage V_{ds} = 1.2 V
  - J = 25 µA/µm

S Parameters

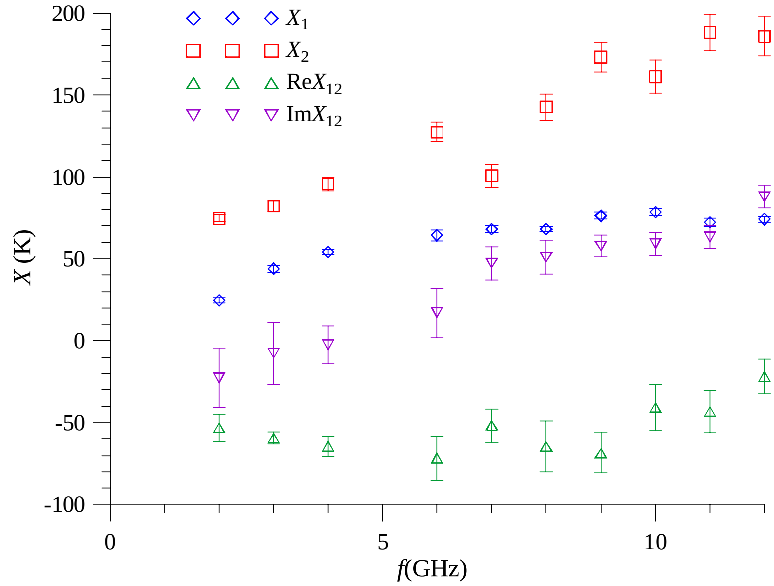


S_{11} at plane D

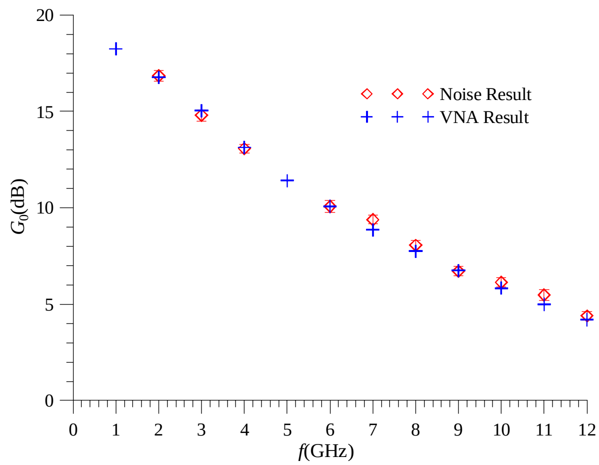
Frequency ranges

RFMD 0.5 – 6 GHz (to cover cellular bands)
IBM: 2 – 26 GHz
NIST: 1 – 12 GHz

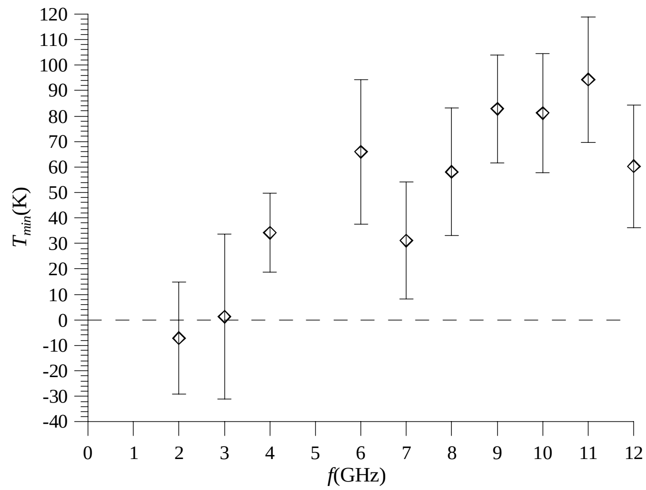
Noise Parameters - X's



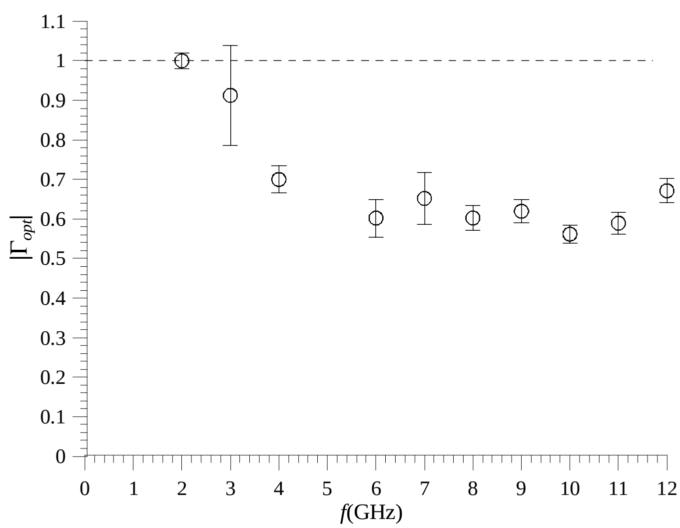
- Get $G_0 \equiv |S_{21}|^2$ from the fit; also measure it (independently) with VNA. So compare the two sets of results.



Meaured values of T_{min}



Meaured values of $|\Gamma_{opt}|$



POSSIBLE IMPROVEMENTS

- Obvious possibility is cal of hot noise source.
- Can also use the Monte Carlo uncertainty program to test possible improvements.
- Caution: results are for NIST methods & system. Expect similar results for other systems, but …
- “Plan” to extend program to more common or more general systems & methods.
- Possible improvement: Use of a cold (i.e., $<<T_{amb}$) input noise source.

NIST NOISE

SUMMARY

- We measure the noise parameters (with uncertainties) at an on-wafer reference plane, but do not deembed to the transistor.
- Noise performance of the devices we measure (0.12 μm gate length NMOS) is better than our ability to measure it.
- We believe we have ways to improve the measurement techniques.

NIST NOISE

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NIST Noise publications & presentation slides available at

http://boulder.nist.gov/div818/81801/Noise/index.html